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Simulation developments for Spoke superconducting cavities design

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Abstract

In the frame of the HIPPI JRA, which proposed R&D activities meant to foster the development of a common European technology base for the construction of high intensity pulsed linear accelerator, IPN Orsay is involved in the development of the Spoke type superconducting cavities. The 352 MHz 2 gaps Spoke cavity has been proposed by IPN Orsay for beta 0.15 sections, and the 352 MHz 4 gaps Spoke cavity has been proposed by FJZ Jülich for beta 0.65 sections. The important simulation investigations have been realized at IPN Orsay, as the numerical codes adapted for superconducting cavity electromagnetic and mechanical behaviors' studies are different from FJZ laboratory, the simulation results supply confirmations about 4 gaps Spoke design made by FJZ Jülich.

Introduction

Superconducting (SC) RF cavities have much larger efficiency, accelerating gradient and bore aperture than normal conducting (NC) structures. This technology is then expected to be advantageous in a linear accelerator in terms of power consumption, construction cost and beam loss. Although this conclusion is well accepted for the high energy part of the accelerator, this is not the case at low energy, mostly because of the short distance required between transverse focusing magnets, which reduce the energy gain per real estate meter. So for a closed beta, several alternative solutions have been proposed and optimized. All the cavities developed in the HIPPI project are designed in the pulsed mode, the sensitivity to the Lorentz forces is especially critical. It is therefore of high importance to improve the simulation tools which play a really important role in the prediction of Lorentz forces detuning of superconducting cavities. It is thus of high importance to reduce as much as possible the effects of the Lorentz forces detuning for the cavities. The use of several elements in the design such as stiffening rings ribs or tuner to enhance the stiffness of the cavities require optimization and simulations controls. Finally, these studies are helpful to determine the lowest energy at which low beta superconducting cavities could safely and economically operate.

1. SIMULATION PLATFORM AT IPN ORSAY

1-1. MULTI-PHYSIC BEHAVIOUR

Superconducting RF cavities are formed of niobium walls in which a high electromagnetic field is established in order to provide a longitudinal electric field at the axis of the beam pipe. One of the principal advantages of this structure is its capacity to obtain a high accelerating gradient in a limited distance, minimizing the linear accelerator length. But as a consequence, the level of the electromagnetic field at the inner surface of the niobium wall can be very high; the induced Lorentz forces can become critical for the stability of the resonator. In fact, the Lorentz forces deform the cavity wall's structure, and consequently, the resonance frequency is shifted in a few milliseconds while the electromagnetic field establish instantaneously in the cavity, this phenomena can drive the RF cavity out of stability. For this reason, the prediction and the control of the Lorentz forces detuning is fundamental in the design of the superconducting cavity.

The most significant difficulty concerning the Lorentz forces detuning studies is the result of multi-disciplines behaviours involved and coupled. First, a preferment CAD tool is necessary for the design in all full 3D problems. Starting with the CAD computer design, the electromagnetic optimization must be performed in the vacuum space contained inside the cavity wall, simultaneously, the structure analysis should be performed on the cavity wall modelled with shell and/or volume elements, so the simulations are completed considering the wide aspects to cover and their interconnections.

The major work developed at IPN Orsay consists in creating a platform for the simulation tools, which offers an additional dimension to the traditional specific codes for each specific domain (Catia for CAD design, Cast3m for mechanic calculations and Soprano/Opera for electromagnetic simulations), makes the coupled simulations instantaneously and gives a global vision of the multi-physic problem. The choice of each specific simulation tool is based on the existent codes at IPN Orsay, this guarantees the reliability of some well know tools confirmed in past experiences and reduces the financial investment. Finally, the

simulation results can cross-confirm the design studies realized with commercial codes like ANSYS and others.

1-2. PLATE-FORM'S CONFIGURATION

The most important investigation consists in developing a platform which allows the instantaneous linkages between CAD, mechanical simulations and RF simulations.

The difficulty is to assume the compatibility of different models used for different physics problems: for electromagnetic, the simulation model is constructed on the cavity inner volume while the mechanical analysis model is constructed on the cavity wall. The mechanical simulation depends on the results of the electromagnetic simulation which determinates the electromagnetic field distribution – and thence forces – on the inner surface of the cavity wall. The crucial point is to transfer these simulation results obtained on the vacuum volume model to the cavity wall model.

This situation determinate the global strategy to make the coupling between mechanical simulations and the electromagnetic simulations: to avoid all problems in terms of the field interpolation or any lost of the numerical precision due to the field transfer between one code to another, the two models used in two different simulations codes should have the same modelling in the common surface which is at same time the inner surface for the cavity wall and the envelop of the vacuum space.

As an additional aspect, we can consider two kinds of model in structure analysis: the cavity wall could be modelled with a shell model under hypothesis of the thick wall or with a volume model. In the case where the simulation concerns only the cavity wall without any additional stiffener, the shell model is simpler to use than the volume model. But in case the stiffeners are necessary, the volume model is more adapted.

The development of the global platform is based on an adequate solution which integrates multi-physic tools with all specific constrains; three groups of interface programmes have been developed:

- Interface between CAD code Catia and electromagnetic code Opera
- Interface between CAD code Catia and mechanic code Cast3m
- Interface between electromagnetic code Opera and mechanic code Cast3m

First, the cavity's design is drawn by Catia. In addition, Catia can make the structures modelling by finite elements. The vacuum space can be meshed by tetrahedrons. The advantage is the easiness of the modelling directly connected to the design: no problem for interpretation of the geometry; time saving.

Opera 3D is a software for electromagnetic design. One of its modules Soprano is a specialized analysis module for finding the frequency domain fields, or resonant modes (Eigen values) of a structure. In addition to its own modeler, Opera 3D has a Pre Processor which is able to read external modeling written in IDEAS-Universal format.

The interfaces programmes assure the transfer of all geometry data and the connectivity of elements. More, the interfaces programmes create all surface elements coherent from the tetrahedrons volume modelling for the specific electromagnetic boundary conditions definition: prefect reflexion wall...

Another group of the interfaces programmes consists to elaborate the compatible model for mechanical simulations with Cast3m code. The essential matter is to assure the coupling of the electromagnetic analysis with the structure analysis. Here, the interfaces programs offer two possibilities: in case there is no stiffener on the niobium wall, the interfaces programmes built the shell triangular elements model for the cavity all from the Catia's tetrahedrons volume for the vacuum space; in case the stiffeners are used, the cavity wall is modelling at first by the Catia modeller with tetrahedrons volume elements, transferred through the developed programmes to Cast3m, then the inner surface elements are shorted by the

interfaces programmes to form the envelop of the vacuum space, which is modelling by Cast3m modeller for electromagnetic simulations. These models were imported to Opera 3D via the third group of the interfaces programmes.

The last group of the interfaces programmes assure the linkage between Cast3m and Opera 3D. The principal functions are, at one side, to transfer the electromagnetic distribution at the inner surface of the cavity wall from Opera to Cast3m, and at the other side, to deliver the deformed cavity geometry due to Lorentz forces from Cast3m to Opera. The basic support is the common meshing of the inner surface of the cavity wall and envelop of the vacuum space. So, if the cavity has not any stiffener, the vacuum space modelling is elaborated by Catia and imported to Opera 3D, the surface elements of his envelop as well as the electromagnetic field after Opera 3D simulations are shorted by interfaces programmes and imported to Cast3m. If the cavity is equipped the stiffeners, the cavity wall modelling is elaborated by Catia at first, the surface elements of the inner surface elements are shorted by interfaces programmes and imported to Cast3m, the Cast3m modeller make the vacuum space modelling from the inner surface elements and this modelling is exported to Opera 3D for electromagnetic simulations.

The interfaces programmes share a set of libraries in which some basic data have been stocked from Catia modelling. So the program is based on objects architecture.

2. MULTI-GAPS SUPERCONDUCTING SPOKE CAVITY

The 352 MHz $\beta=0.48$ multi-Spoke type cavity has been designed by the FZJ Jülich laboratory [1]. The design takes account at first of the electromagnetic optimizations, in order to reach the highest accelerating efficiency [1]. The triple-spoke is made of niobium and defined as a multi-gaps H-cavity. Some parameters of the cavity are listed in table 1.

Parameter	Values	Units
Frequency	352	MHz
$\beta=v/c$	0,48	
Number of gaps	4	
R aperture	2,5	cm
$\beta\lambda/2$	20,44	cm
Rcav	21,7	cm
G	93	Ω
Epk/Eacc	4.65	
Bpk/Eacc	10.97	mT/MV/m

Table 1: some parameters of triple-Spoke cavity

The figure 1 shows the first HIPPI triple-Spoke prototype with a stiffening system realized by FJZ Jülich. The cavity wall is made up of a cylindrical outer conductor. Three spoke tubes, rotated by 90 degrees from one to the next, are picked on the cylinder. The end cell of the cavity is conical, to minimize the magnetic field on the spoke surface.

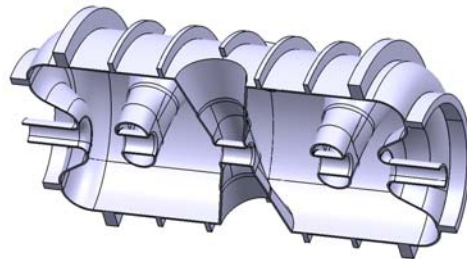


Figure1: Triple-Spoke cavity's design with Catia

The stiffeners on the prototype consist in five niobium ribs (10mm x 20mm) welded on the cylindrical body, two rings (18mm x 40mm) welded at the extremities of the cylinder and a niobium ring (18mm x 35mm) at each end cup.

2-1. MECHANICAL BEHAVIORS

The first mechanical issue concerns the deformation of the cavity wall under vacuum conditions. For the simulation with Cast3m, the niobium structure is modeled by tetrahedrons finite elements. The developed interface programs allow carrying out the geometrical analysis and rearrangement of the Catia meshing into a specific Cast3m meshing, figure 2.

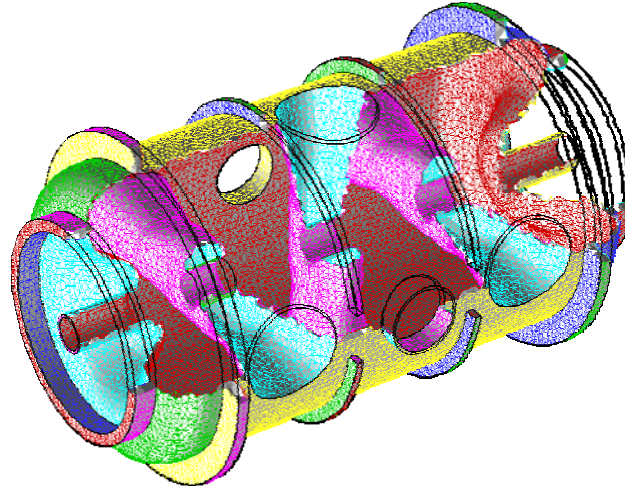


Fig. 2: triple-Spoke cavity wall's meshing

The atmospheric pressure applies on the external wall and deforms the cavity. Two important parameters should be evaluated, the maximum von Mises stress and the resonance frequency shift due to the deformation.

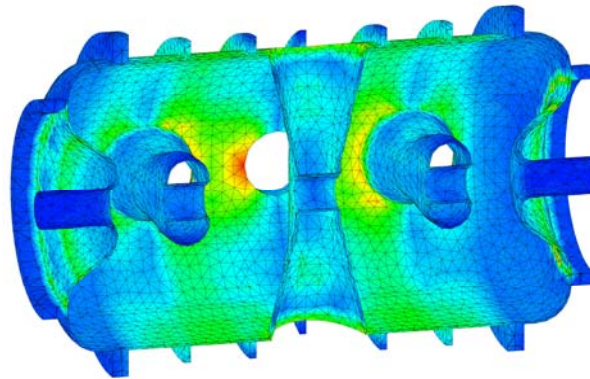


Fig. 3: Von Mises stress distribution, maximum < 18 MPa

The parameters concerning the stiffeners and the results of simulations are listed in table 2.

Cavity wall thickness	4 mm
End cup stiffener	18 x 35 mm x mm
rings	18 x 40 mm x mm
ribs	10 x 20 mm x mm
Maximum displacement	0.015 mm
Maximum von Mises stress	18 MPa
$\Delta f / \Delta P$	-9.24 Hz/mbar

Table 2: triple Spoke cavity under external pressure

The stress distribution is shown in figure 3. The stress peak is about 18 MPa, largely lower than the elastic limit of the niobium (near 50 MPa at room temperature).

The mechanical dynamics simulations have also been performed to find the structure's eigenmodes. In pulsed regime, these eigenmodes could be excited by external noise which is harmful. In general, the first mode should be controlled to be sufficiently high to avoid all risk of excitation due to environment noise.

The most significant conclusion from simulations concerns the essential role of the way of fixing. The first eigenmode of the cavity is much higher in case where the cavity is fixed by external stiffening rings on the cylinder compared to the case where the cavity is fixed by his beam pipe, table 3.

mode	Cavity fixed by beam pipe	Cavity fixed by rings on cylinder body
1	49 Hz	578 Hz
2	144 Hz	669 Hz
3	145 Hz	686 Hz
4	160 Hz	828 Hz
5	161 Hz	843 Hz
6	202 Hz	887 Hz

Table 3: triple-Spoke's eigenmodes

The simulations show that it is very important to block the cavity at the external wall of the cylinder body in order to prevent the rotation mode around the axis. The first prototype is hold by the rings on the cylinder body, in this way the cavity is largely stabilized, the risks to excite the eigenmodes are minimized.

2-2. COUPLED MECHANICAL-ELECTROMAGNETIC SIMULATIONS

Multi-disciplinary behaviours are involved concerning the Lorentz forces detuning simulations. In general, the first estimations are based on the cavity without any specific stiffening systems, but it's judicious to plan from the beginning the studies about the stiffeners design. Usually the stiffeners are added at the external surface of the cavity wall whose geometry becomes more complicated. But electromagnetic simulations are based on the vacuum space inside the inner surface of cavity wall, this surface is the only part common to the mechanical model and electromagnetic model. To limit errors in the coupling of the mechanical-electromagnetic simulations, the strategy is to use the same mesh at the inner surface of the cavity wall for both models. With this in mind, the modelling starts with the mechanical model of the bulk cavity. The interface programs have been developed with the possibility to extract the surface zones from volume elements. This way, the envelop of the vacuum space for electromagnetic simulations can be extracted from the mechanical model, then the vacuum space model is build from this envelop by Cast3m modeller.

The electromagnetic fields distribution has been simulated using Opera3d/Soprano on this vacuum space model. As the Lorentz forces depend from the electromagnetic field distribution at the inner surface of the cavity wall, only this part of the electromagnetic field distribution is transferred back to Cast3m via the developed interfaces programs. Then the radiation pressure and the mechanical deformations on the cavity wall modeling are calculated with Cast3m.

The Lorentz forces depend on the electromagnetic field on the inner surface of the cavity wall and deform the cavity wall. The radiation pressure which represents the Lorentz forces distribution acting on the cavity inner wall is expressed as the formula below:

$$P = \frac{1}{4}(\mu_0 H^2 - \varepsilon_0 E^2)$$

From the electromagnetic fields distribution on the inner surface of the cavity wall, the radiation pressure has been calculated by Cast3m.

In the figure 4, different models of triple Spoke cavity are presented. The figure 5 shows on the left side the concentration of the radiation pressure, in middle its vector representation and at the right side the deformation of the cavity wall.

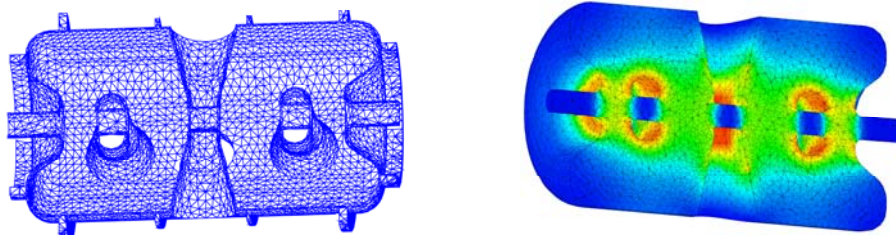


Fig.4: left: cavity wall model (Cast3m); right: vacuum space model (Opera3d)

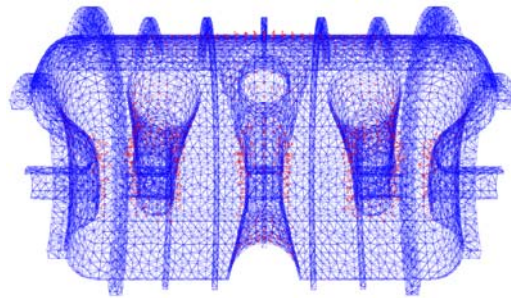


Fig.5: radiation pressure's vector representation

According to the displacements calculated by Cast3m, the vacuum space modelling is actualized taking into account the deformations of the cavity wall thanks to a specific program developed in the interface programs package. From the deformed cavity shape, the new RF simulations are performed on Soprano in order to get the resonance frequency on this model. Finally, one can calculate the frequency shift Δf due to Lorentz forces by $\Delta f = f' - f$. The Lorentz forces detuning factor is defined as the frequency shift over the square of the accelerating field: $\Delta f = K \times E_{acc}^2 (MV/m)^2$. Without any stiffening system, this factor is estimated to be $-5,2 (MV/m)^2$. With the stiffeners system, the factor of the Lorentz forces detuning is much lower, it's reduced to $-1,4 (MV/m)^2$.

2-3. CAVITY STIFFENING

The simulations based on the design of the 1st prototype show the efficiency of the stiffeners in reducing Lorentz forces detuning. Several other methods of stiffening have been proposed by FJZ Jülich, and discussed with IPN Orsay, for example the use of ribs at the end cup, figure 6 left side, or of copper coating at the end cup, figure 6 right side.

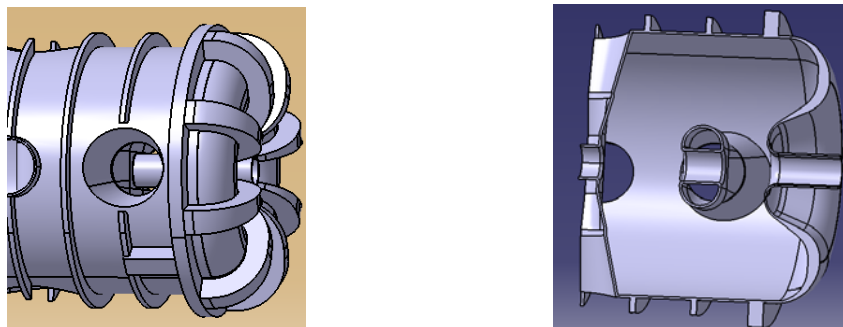


Fig. 6: Cavity stiffening by ribs at end-cups (left side) or by copper coating (right side)

Even if all options aren't to be realized, an interesting observation from simulations results is that all proposed systems produce quite similar results concerning the Lorentz forces reduction, the order of scale for the Lorentz forces factor's reduction using different stiffeners is compared in table 4.

Design	Δf (Hz/(MV/m) ²)
without stiffener	-5,3
Prototype's stiffeners	-1.4
ribs on end cups	-1,3
Cu on end cups and Nb ribs on body	-0,9

Table 4: reducing Lorentz forces detuning with different systems

3. TWO-GAPS SUPERCONDUCTING SPOKE CAVITY

The two gaps Spoke cavity has been studied by IPN Orsay for the low beta section (beta 0.15). Some cavity RF parameters are listed in table 5.

	2 gaps Spoke cavity
Number of gaps	2
Frequency [MHz]	352
Beta	0.15
Bpk/Eacc [mT/(MV/m)]	7.95 / 11.94
Epk/Eacc	3.24
G [Ohm]	89
Lacc [mm]	128
Optimal beta	0.2

Table 5: 0.15 two gaps Spoke cavity RF parameters

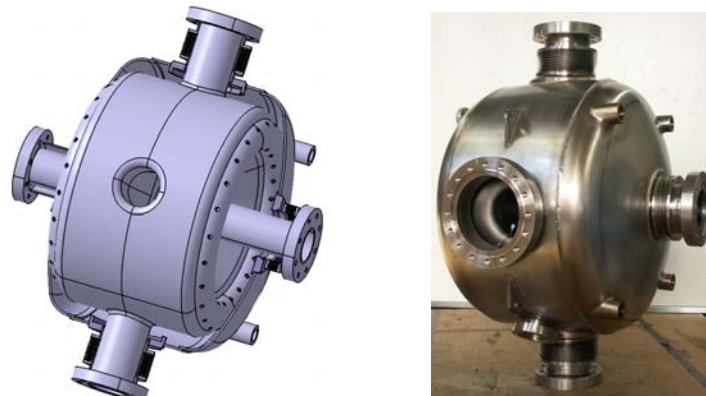


Fig. 7: stiffened 2 gaps Spoke cavity with its helium vessel

The 2 gaps Spoke cavity prototype, figure 8, is built with RRR 250 3 mm thick niobium sheet. The cavity has been stiffened by semi-tube in front of each end cup. The helium vessel is made with stainless steel, it is connected to the cavity by stainless steel bellows.

Simulations are performed at IPN Orsay using the platform of calculation involved previously,

3-1. MECHANICAL BEHAVIORS

The cavity's mechanical behaviours under external 1 bar pressure have been studied. Two extreme situations have been taken into account: the case where the cavity is totally constrained and the case where the cavity is free.

The distribution of Von Mises stress at the cavity wall is shown in figure 9, the pick of the stress level is reduced thanks to the stiffener on the end cups. The maximum level of the stress doesn't exceed 34 MPa.

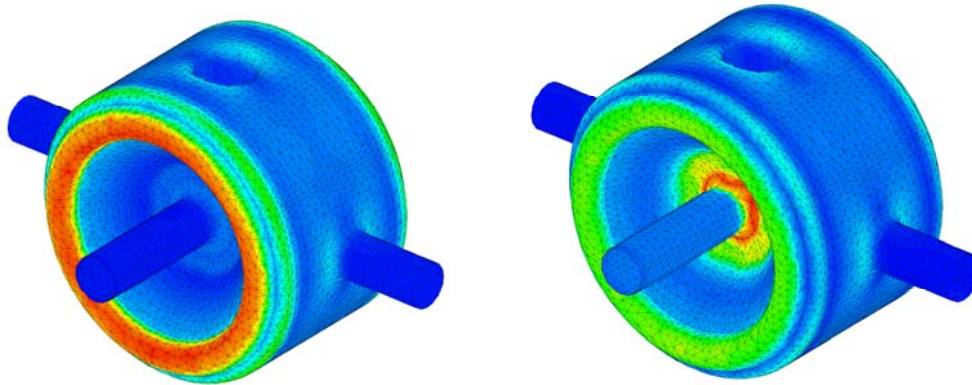


Fig. 8 : Von Mises stress distribution on the cavity wall: left cavity free; right: cavity fixed

The vacuum load at room temperature is performed on the prototypes, the displacements and the frequency shift have been measured. In these tests, the cavity is free, so the measured values are compared to the simulations results in the same conditions.

	Simulations (Nb=3mm)	Measurements (Nb < 3mm)
Max displacement (mm)	0.2	0.17
Max Von Mises stress (MPa)	34	NA
Frequency shift (kHz)	-140	-440

Table 6: mechanical parameters under vacuum

The prototype has been subjected to chemical treatment, its thickness isn't uniform and somewhere the thickness is less than 2 mm, while in the simulation the cavity wall is supposed to be uniform with 3mm everywhere.

3-2. LORENTZ FORCES DETUNING SIMULATIONS

With the same procedure used for multigaps Spoke cavity, the modelling starts with the mechanical model constructed on the cavity wall. The electromagnetic fields distribution has been simulated using Opera3d/Soprano on the vacuum space modelling.

The distributions of electromagnetic fields at inner surface of the cavity wall are presented in figure 9.

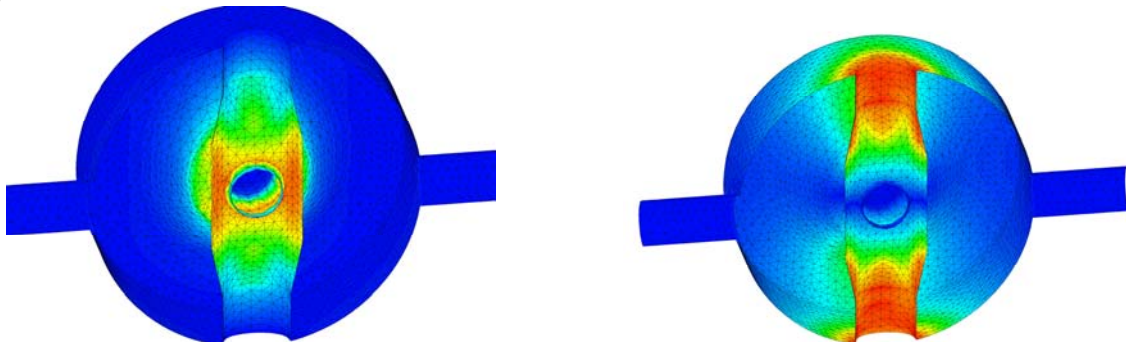


Fig. 9: electric field (left) and magnetic field (right) distributions at inner cavity surface
The simulation results are listed in the table 7.

Simulation results	2 Spoke IPN
Cavity stiffness K [kN/mm]	24
Tuning sensitivity $\Delta F/\Delta l$ [kHz/mm]	964
Frequency shift with fixed ends [Hz/(MV/m) ²]	-20
Frequency shift with free ends [Hz/(MV/m) ²]	-72
Pressure sensitivity [Hz/mbar]	41(fixed ends)/140(free ends)

Table 7: principal simulations results

3-3. COLD TESTS MEASUREMENTS

Several series of tests were carried out on the 2 gaps Spoke prototypes at IPN Orsay in a vertical cryostat at 4.2K. The tests conditions are quite similar to the free ends conditions since the cavity has been put inside a vertical cryostat. The simulation results provide the possible range between the totally free cavity at one side and the completely constrained cavity at the other side.

After simulations, the predicted Lorentz forces detuning factor is estimated to be -20 Hz/(MV/m)² in case where the cavity is totally constrained and to be -72 Hz/(MV/m)² in case where the cavity is free.

The measured Lorentz forces factors are situated between -55 Hz/(MV/m)² to -47 Hz/(MV/m)², good agreements between simulations results and experimental data have been observed.

3-4. DYNAMIC ANALYSIS

Mechanical dynamic simulations have also been performed, the cavity is fixed by the beam pipes. The five first eigenmodes are listed in table 8.

mode	Cavity fixed by beam pipe
1	118 Hz
2	163 Hz
3	177 Hz
4	211 Hz
5	212 Hz

Table 8: mechanical eigenmodes of 2 gaps Spoke cavity

In this case, the cavity is fixed by its beam, the first mode (118 Hz) is quite low, this mode is a rotation movement around the beam axis.

4. OBSERVATIONS

Even if the 2 gaps Spoke cavity and the 4 gaps Spoke cavity are designed for the same resonance frequency, 352 MHz, but two different beta (0.15 and 0.48 respectively), the similar studies in mechanical behaviors and about Lorentz forces detuning suggest some observation on the results for the same parameter.

	2gaps beta 0.15 Spoke prototype (3mm)	4 gaps beta 0.65 Spoke prototype (4mm) with stiffener
Cavity stiffness	24 [kN/mm]	26 [kN/mm]
Tuning sensitivity	964 [kHz/mm]	226 [kHz/mm]
k_L with stiffeners, fixed ends	-20 [Hz/(MV/m) ²]	-1.4 [Hz/(MV/m) ²]
Pressure sensitivity, fixed ends	41 [Hz/mbar]	9.24 [Hz/mbar]
Maximum stress	34 MPa	18 MPa

Table 9: comparison of simulation results for two Spoke cavities

The prototypes of these two kinds of Spoke cavities haven't the same thickness, the choice of the thickness is also suggested by the cost. But, it seems that the 3 mm 2 gaps Spoke prototype is much more sensible to the pressure on the cavity's wall than the 4 mm 4 gaps Spoke prototype, the frequency shift due to the external pressure is four times higher for 3mm 2 gaps cavity than for the 4 gaps 4 mm cavity. The same remark could be observed concerning Lorentz forces detuning factors. In parallel to this, the tuning sensitivity is four times higher for the 2 gaps prototype.

Another important remark concerns the mechanical eigenmodes. It seems if the cavity is fixed at the outside outline of the cylinder body, as shown in this report for the 4 gaps Spoke prototype, the first eigenmode is very high, it means the cavity is very stable versus external vibration excitations. In case the cavity is fixed on the beam pipe, as shown here for the 2 gaps prototype, the lower modes appear. The way of the cavity's fixation influences significantly the level of the first eigenmode.

Conclusion

IPN Orsay is involved in the studies and developments of the Spoke type superconducting cavities for HIPPI project since 2004. Important efforts have been put on numerical simulations in order to give the theoretical prediction for some fundamental parameters such as Lorentz forces detuning factor. Multi-physics analysis has been performed thanks to a platform of simulation tools interconnected by interface programs. Some simulation results have been compared with the experimental results realized on the first prototypes.

It is important to underline the fruitful collaboration between FZJ Jülich laboratory and IPN Orsay on the 4 gaps multi-Spoke 352MHz beta 0.48 cavity's studies. The results presented in this document confirm substantially the simulations made at FZJ simulating the expected performance with other simulations tools.

References:

[1] E. Zaplatin et al, Design of a triple-Spoke cavity for 352 MHz and beta=0.48, CARE-Note-2006-001HIPPI, Cern Document, 2006.

Acknowledgements

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